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CONTENTS

ABSTRACT

A brief historical account is given of operations research (OR), and computer hardware and software. OR and computers may cooperate in heuristic problem solving and interactive man - machine systems, especially relevant for ill-structured problems. Obtaining data, as opposed to model building and solution techniques, is facilitated by the installation of terminals, and modern data base management systems (DBMS). Remain the questions of how to use data, and more difficult, which data to collect. This requires a cost/ benefit analysis of the Management Information System (MIS) structure and the quality aspects like timeliness and accuracy of information. Relevant tools are Bayesian decision analysis or Information Economics, Industrial Dynamics, simulation and gaming. The technical performance of the computer per se can be evaluated using queuing theory, simulation, and other OR tools. Seventy-four references are given for further study.

OPERATIONS RESEARCH AND COMPUTERS

INTRODUCTION

In this contribution we shall survey the interface between operations research (OR) and computers. We assume that the reader has a basic understanding of computers, so that we do not explain elementary concepts like Central Processing Unit but we do briefly discuss concepts like Data Base Management Systems. It is further assumed that the reader has an elementary knowledge of operations research and management science. Hence we do not define techniques like linear programming (LP), simulation, and so on. We do include a section with a brief survey of the OR field, i.e., its organizations, literature sources, etc. In the remaining sections we emphasize how OR techniques, models (theory), and practice are affected by the developments in the computer field. Conversely, we shall examine how OR techniques are influencing the design of computer operating systems, Management Information Systems, etc. Note that in our terminology we do not distinguish between OR and management science, though some people may prefer not no use the two terms interchangeably. Other publications on computers and OR can be found in the references, but they have a more limited scope than our survey; see [3, 25, 30, 32, 50, 71].

The interface between computers and OR may be studied at different levels:

(1) The computer system itself requires scientific design, analysis, and tuning. For instance, we may study how many terminals can be connected to the CPU without endangering the response times. An important aid in answering such questions, is the collection of mathematical techniques and models provided by OR, for instance, queuing theory

and simulation.

(2) The user of a computer may use computer services for either data processing (say invoicing) or decision-making. The computer's role in decision-making is twofold:

(i) Scientific computation: The computer is primarily engaged in CPU activities; input/output activities are minor. This is the area of number crunching as in linear programming, simulation, regression analysis, etc.

(ii) Management Information Systems: The computer's main job is not computation but data capture, storage, sorting, retrieval, and display. This is the area of the traditional Electronic or Automatic Data Processing (EDP, ADP), and modern Data Base Management Systems (DBMS). This capability may provide the data needed as input into OR models.

Interactive man-machine systems form an interesting combination of both capabilities. These Decision Support Systems will be discussed at some length because of their growing practical importance.

(3) Higher level management may be assisted by OR in both the design and the cost/benefit evaluation of computerized information systems. The design of information systems may use OR in order to decide which data to collect, and how to use these data. The cost/benefit evaluation requires mathematical techniques to decide on the desirability of information quality characteristics like accuracy and timeliness, and on the structure of the information system.

We discuss the OR/computer interface first from the OR perspective, then from the computer perspective, giving 74 selected references for further study. We have organized our material into the following sections:

The History of Operations Research

Interactive Systems and Heuristics

THE HISTORY OF OPERATIONS RESEARCH

We do not think that the reader is helped very much by a formal definition of OR. We rather assume that he has an intuitive idea of what OR amounts to. Isolated OR work can be traced back to the beginning of this century, a famous example being the Economic Order Quantity (EOQ) inventory model. However, OR as such started during World War II in Great Britain and the USA; [19, 68]. Shortly after the war professional societies for OR were founded. In the USA these were the Operations Research Society of America (ORSA), and The Institute of Management Sciences (TIMS). In Great Britain it was the Operational Research Society. The countries of Western Europe, Japan, Israel, etc., followed with similar societies. International cooperation among these societies is organized in the International Federation of Operational Research Societies (IFORS). Many more organizations are active in the field of OR/MS, too many to list here.

Publications on OR are staggering. Each society has its own journal. There are journals devoted to specific application areas like inventory control and transportation research, and to specific techniques like simulation and mathematical programming. OR articles can also be found in related disciplines like Computer Science, and Engineering. Abstracts of many OR publications are published in International Abstracts in Operations Research, and Operations Research / Management Science; see also Computing Reviews.

At the same time that OR got started, computers were invented. Detailed historic accounts are given in [4,28].During its short history the computer has shown dramatic increases in CPU and main-memory speeds.

For instance, in the 1950's, 1960's, 1970's respectively, the average speed of main memory was about 10, 1, and 1/10 to 1/100 of a microsecond. Besides speed increases, spectacular improvements in memory size occurred: 1950, 1960, 1970 main-memory capacities are roughly 0.1 million bits, 5 million, 1000 million bits. On-line secondary memory like discs has been integrated with main memory using virtual memory techniques. While computer hardware capabilities showed great improvements, the costs per unit decreased! For instance, memory cost per bit decreased from 100 cents to 10 cents, and then to 0.1 cents. Two phenomena explain these decreasing costs, namely economies of scale (bigger machines are cheaper per production unit) and technological progress (introduction of Large Scale Integration, etc.). Software has not shown such spectacular improvements: Diseconomies of scale may occur, and rising labor costs are not offset by productivity increases. These developments resulted in rising software costs, both absolutely and relative to hardware costs: The software share in data processing costs increased from 5% to 50%, and is now 75%. There are several approaches to mitigate this software problem:

(1) High-level programming languages decrease the programming effort, at the expense of increased compilation and running times, and increased memory space. In other words, expensive labor is replaced by cheap hardware.

(2) Software packages have become available for a great many standard applications like inventory control, linear programming, corporate modeling, etc.

(3) Control over computer projects has been improved by the introduction of procedures like ARDI (Analysis, Requirements Determination, Design and Development, and Implementation and Evaluation). Several more or less ambitious procedures have been developed; for SOP, TAG, ISDOS, etc., see [17]. Programming itself can be organized modularly, and can be done in the form of "structured

programming". The scheduling of computer projects can use OR techniques like PERT.
(4) The useful life of a project is extended by modular programming, high-language programming, Data Base Management Systems (independence of data and languages), emulation, etc.
For additional discussion and references on the approaches (1) through (4) we refer to [23, 36].

What was the impact of these computer developments on OR? Many OR techniques requiring extensive computational work, have become feasible through computer technology. An example is simulation that has become the OR technique most used in practice; see the sample surveys in [63,70]. Linear programming is another example of an OR technique requiring high computational speed, and sizable memory space; see [3]. Notwithstanding the computer's speed practical problems remain. For example, integer programming may still take too much computer time; [19]. Simulation of all possible system variants will remain impossible because the number of combinations "explodes" rapidly; [35]. OR has come in the reach of smaller companies as far as the computer technology is concerned: relatively inexpensive big computers, availability of mini-computers, standard application software. Obviously computer technology is not enough; we shall return to management acceptance later on. In the following section we discuss a development in both OR and computers that can bring the combined forces of OR and computers to the manager.

INTERACTIVE SYSTEMS AND HEURISTICS

Heuristic methods do not guarantee optimal solutions. They may limit the search for a "satisficing" solution by reducing the number of alternatives to a manageable size;[54,p.136] . Examples are provided by hill climbing methods like steepest ascent. Heuristic solutions may be obtained by solving models of a more limited scope. For instance, the Economic Order Quantity in inventory problems may be determined under a number of quite restrictive assumptions: no stochastic demand, no multi-level warehouse system, etc. The resulting square-root formula may then be applied in a practical inventory system, as a heuristic approximation. Heuristic methods are based on common sense, intuition, inside knowledge, trial-and-error, and the like. Two interesting application areas of heuristics are:

(1) Combinatorial problems

The number of alternatives can be so large that even a supercomputer cannot check all combinations. Dantzig [19] gives the following example: If a computer has to check each of 70! combinations ($70! \approx 10^{100}$) and executes 10^6 operations per second, then it will take 10^{37} years to examine all combinations. Such situations can be found in job shop scheduling, travelling salesman, plant layout,and depot allocation. These problems require sophisticated mathematical analysis to come up with practical algorithms.

(2) Ill-structured (ill-defined) problems

In many practical situations the problem is how to define the problem! There may be no unique criterion and there may be fuzzy restrictions and relations.

In the computer field we are confronted with both types of problems. The design and evaluation of an operating system for a modern computer with time-sharing and multi-programming is usually treated as a well-defined problem with great mathematical complications. Management Information Systems lead to ill-structured problems where the major difficulties are not mathematical. More on heuristic methods in general can be found in [49] , and in the contributions by Little and Thompson in [54] , and by Newell in [3]. More specifically we wish to examine developments in computer technology which stimulate the increased usage of heuristic methods.

Modern computer systems permit us to replace the batch mode of operations by the on-line, real-time mode. Consequently, the user may interrupt the computer process, i.e. give new instructions depending on intermediate output. In this way man-machine interaction is created. This "conversational" computer usage enables the machine and the human partner to do that part of the job for which they are best qualified. The computer is fast, accurate, and has a large memory capacity for non-structured quantitative data. Man has a unique capability for creative thinking, learning, pattern recognition, association, intuition,and the like. Interactive computer usage can mean two things:

(i) Interactive programming, including debugging.
This means that after each line of computer code, the computer translates this code into its machine language, and tries to execute the resulting command. (Several lines of codes may be combined to form one command: subprograms, functions.) Technically this process requires a so-called interpreter instead of a compiler.

(ii) Interactive use of an existing program.
The user may have to specify parameters only for an existing standard model, say a simulation model for a class of computer systems, or a LP model.

Let us have a closer look at the way OR model building and solution are affected by interactive computer systems and heuristic solution techniques, resulting in socalled Decision Support Systems.

(1) Model formulation
The user starts with an initial model for his system of interest and tests the output coming available on-line:

debugging, verification (does the program do what it is meant to do, say, generate exponentially distributed variables), and validation (does the model reflect the real system). Depending on these tests, the user may change the program, or proceed to solve the model, or extend the scope of the model. Interactive simulation is discussed in [42, 65].

(2) Model scope

The scope of the model may be restricted because of two reasons. One reason concerns efficiency. Certain real-life activities occur only rarely, say machine breakdowns in a production planning model. If the rare event occurs, an ad hoc solution can be used. We recommend [47, 48] for additional discussion of this issue. The other reason may be that the real-life system comprises subsystems that are not well-defined, well-programmable. In personnel assigment models we may exclude certain qualitative elements like compatibility of persons, and leave it to the user to incorporate these elements. At the higher levels of management many such unstructured decision problems exist: warehouse location, sales and capacity planning, etc.

(3) Model solution

The human partner can play various roles in the man-machine system:

(a) The user may specify only the intitial solution (starting point) whereupon the computer takes over, using an algorithm like LP. In hill-climbing methods like steepest ascent such initial solutions must always be given by the human partner. In LP the initial solution supplied by the human partner may drastically speed up the progress to the optimum. In a LP program for, say, an oil refinery the initial solution can be based on "yesterday's" optimum solution.

(b) In truly interactive systems the human role goes much further than in case (a). The user specifies a solution, using his intuition, prior knowledge, etc. Then the computer with its computational speed and consistentency computes the consequences, using its program, i.e. a model that may be very complicated including non-linearities, discontinuities, and stochastic variables. Next the human partner is active again, evaluating the solution consequences. He may apply multiple criteria, incorporate fuzzy (qualitative) restrictions, side-effects, and so on. Note that the computer may also reveal that the user's solution is conflicting with previous user solutions, or is infeasible. After evaluating the solution, the user may come up with a new solution, and we cycle back. Finally, the user decides to terminate because he is satisfied with the last or one of the previous solutions. This is not necessarily "the" optimal solution as it is the result of a heuristic approach to a , possibly ill-defined, problem. Examples of type (b) are provided by many practical simulation studies, at the operational and the tactical/strategic level.
It is interesting to see how the role of the computer can be expanded in man-machine systems. The computer can try a number of solutions "around" the solution proposed by the human partner. In [61] an example is given where the computer systematically examines the solutions around the user's suggestion for the allocation of, say, bus terminals in a city. A different approach is to have the computer find a solution for a simplified model; this solution may guide the user in his proposals. Note that it would be much more ambitious to have the computer learn from its past experience: artificial intelligence.
(c) Not inspired by OR is the approach where the computer does not use models but just contains data. As we shall see in the next section a modern DBMS enables the computer to combine data, search for specific data, and so on. The

user can query the data base in a "user friendly" language. The communication may be aided by menu selection (multiple choice from computer suggestions replacing user programming), lightpens, visual displays in color, etc. An example is a geographical data base which, per basic geographical area (street), gives data on population, income, crime, etc. The user can draw "districts" whereupon the computer retrieves the statistics per district, say total buying power or total number of crimes. Applying a mental model the user can evaluate the configuration of the districts. Next he may try a different configuration, and cycle back until he is satisfied with a configuration. Applications are supermarket site selection, police zone specification, transportation studies, urban planning and military studies; [13].

The developments in model building and solution have reduced the practicality gap between management science (or OR) and management practice. In real life the interest is not so much in sophisticated optimization algorithms as in"what if" questions (satisficing solutions). The user may get more involved in both building and solving the model. Interactive simulation packages are customized by having the user specify parameter values for <u>his</u> system. Geographical data bases have been used by police officers and school officials, without the assistance of professional programmers. Ill-defined problems at the strategic and tactical level are currently attacked by corporate models, i.e., financial models based on the company's balance sheet and profit & loss account. These models are formulated as interactive simulation studies; [47,48,53,62]. The selection of advertising media using a maximum-seeking heuristic is operational in the MEDIAC system; [40]. Interactive simulation for city planning combining demography, employment, transpormation, utilities and communications is described in [27]. More applications can be found in the references [11, 33, 55].

MANAGEMENT INFORMATION SYSTEMS

Management Information Systems (MIS) form a subject on which much has been written. Therefore we shall have to limit our discussion drastically, emphasizing the interface between MIS and OR. Whereas the previous section stressed the computational capability of computers, the current section concerns the computer's capability for data capture, storage, sorting, retrieval and display. This capability used to be associated with the term Automatic or Electronic Data Processing (ADP, EDP). Nowadays the catchword is Data Base Management Systems (DBMS). Whereas OR books mainly discuss techniques, the OR practice is characterized by serious problems in finding the necessary data. Computers can be helpful in this problem area.

In order to improve the data collection problem radically, it is recommended to have on-line data capture at the source. As an example let us consider self-service retail stores [56,59] . At the supermarket's checkout sales transactions per item can be recorded by point-of-sale (POS) equipment, i.e. electronic gear that can read price tags automatically, store the data, and produce a sales slip for the customer. In this way management obtains data that are timely, detailed (per item),and accurate (no cashier's errors). These data enable management to evaluate the effects of, say, price changes and sales promotions. These data also yield the information needed for inventory management: sales volumes and prices for as many as a million articles or "stock keeping units". It also becomes possible to have more frequent inventory reviews; see [36] . Other applications of on-line data collection can be found in banking offices, travel agencies, manufacturing plants, and so on;[47,73] . Data for OR models are readily available if such models are imbedded in a MIS. Examples are simulation models for production planning and maintenance, and LP models for integrated sales, production and capacity planning; [32 ,47] . These developments do not mean that all data needed are available from now on! Quantitative data at the operational level are easy to capture, but qualitative data (the worker's mood, loss of goodwill) remain hard to measure and to collect, most times. Strategic data concern the company's environment (competitors, customers, government, labor unions, stock market), and are not collected routinely. Which data to collect (including its level of detail and the like) is a problem to which we shall return below.

In the preceding paragraph we emphasized the collecting of data. However, data must also be retrieved and presented to the user as needed. This is the area of Data Base Management Systems. Without a DBMS the computer system has a number of files (ordered collections of records), for instance, one file on inventory and one on accounts receivable. Certain data (say, quantity sold) occur in more than one file. Hence data is duplicated, and cannot be updated simultaneously (inconsistent data). A DBMS means that data occur only once. Relationships among data items are created by links or pointers (the address of the related record is stored in the current record). Physically (as opposed to logically), the records are stored on random access devices like discs. In one example storage requirements were reduced from 50 to 5 billion bytes [10] . Note, however, that redundancy of data (multiple copies) does have the benefit of increased reliability. Redundancy may also improve the efficiency of data processing: DBMS software is quite sophisticated, incurring processing and data storage overhead. For instance, creating a new record requires updating all links with other records. For some data on overhead costs see

[21] . From the user's point of view a DBMS should enable him to manipulate data using one or more languages of his choice, say, a problem-oriented query language, or a mathematical procedural language like FORTRAN. Since the data are **logically** organized by links forming data structures like networks and trees, it becomes easy to ask ad hoc questions like "in which products is part A utilized" (Bill of Materials),or "how many employees work in a warehouse receiving more than x articles per month". Such ad hoc questions are to be expected in heuristic man-machine systems and in tactical/strategic, non-routine models. Technically much progress has been made, and a variety of commercial DBMS is on the market, for example, IMS and TOTAL. The literature on DBMS is growing exponentially so that we give only a sample: [14 ,20 ,33 ,34 ,45 ,52] . From the user's perspective many problems remain. From his perspective the DBMS is just a technical part of the MIS.

An ideal Management Information System should have the following technical characteristics.
(1) On-line data capture, but not necessarily on-line data update. A POS system provides on-line data collection, but these data may be stored on tape and transmitted to the central computer once a day only (batch update).
(2) On-line, interactive data retrieval based on user-friendly software like a problem oriented query language. Planned and unplanned (ad hoc) questioning of the data base should be possible using a DBMS.
(3) Security (authorized use only),privacy, reliability (no breakdowns), backup and recovery. We shall not discuss these technical issues here. They are discussed in the DBMS references given above.

In a MIS with on-line data capture each operational activity of the company can lead to the creation or update of records. These operational data can be aggregated to form summary data at the tactical and strategic level: bottom-up approach. From the point of view of the computer/ DBMS enthousiast this seems the way to proceed. The alternative is to base tactical/strategic decisions on corporate models and to collect the necessary data (aggregated corporate data plus external data) in a separate effort: top-down approach; [5, 47]. So in general we are confronted with the problem of which data to collect and how to use them. This is where OR should become of much more relevance than it is nowadays. Ackoff [1] emphasized that managers should not be flooded by irrelevant data, and moreover he claimed that managers do not know which data they really need. The relevance of data is guaranteed if the data are input into a model. The model's scope may be restricted to, say, the inventory and production subsystem, or alternatively, the model may be a total corporate model. The inventory model shows that data are needed on lead times, demand forecast errors, etc. Note that some data must be collected not for decision support but for accounting (clerical) purposes. For instance, the supplier's address is needed to send the invoice. Some historical data must be saved for legal (tax) purposes, but such data can be stored off-line (COM or computer output on microfilm, tape libraries, etc.) The DBMS might also keep statistics on the data usage, and dump data of low usage off-line. (Which data to keep in on-line storage, may require an OR inventory model.) In the next section we shall return to the problem of which data to collect and how detailed, frequently, and so on.

Traditionally OR has been used to decide on how to use data. OR techniques like simulation and LP involve sophisticated usage of data. Interactive, heuristic approaches may mean less sophisticated data manipulation (but may extend the application area of OR towards the strategic level). For a case study illustrating the combination of OR and MIS we refer to [9]. The MIS should also provide follow-up.When later on the actual outcome becomes known the MIS may report on significant deviations between the actual and the expected results. Such a report may lead to corrective action, and may also improve future model efforts. For instance, in investment analysis actual cash flows may be compared to apriori subjective estimates and fed back to the "expert opinion" suppliers; see also [1,47].

The ideal MIS does not yet exist. There are systems that cover specific operations of a company, say, production scheduling and inventory control. There are models for answering specific what - if questions as in corporate simulation models. Rather ambitious projects are under way. The IPSO system is such a project, integrating short and medium term information and control systems for planning capacity and workforce at Philips electronics; [8]. Actual DBMS applications can be found in [10,34]; see also the surveys on MIS in [12,15,69]. Organizations active in the MIS field are the Society for Management Information Systems (SMIS), and the Special Interest Group on Business Data Processing(SIGBDP) of the Association for Computing Machinery (ACM).

COST/BENEFIT ANALYSIS OF M.I.S.

In the present section we discuss the MIS, not from the point of view of its direct users, but from the viewpoint of top-management, which is responsible for the cost/benefit evaluation of the MIS. As we mentioned before, some data are collected for routine accounting purposes like invoicing and salary administration. This part of the information system should be distinguished from the MIS, a decision oriented subsystem. Evaluating computer projects in the accounting subsystem, is relatively easy. A physical product like invoices or payroll-slips is to be produced, and computerization means a more capital-intensive production technique. This problem can be analyzed using traditional investment analysis (Net Present Value, regression analysis for project cost projection, and so on). In [36] we present economic models and techniques for this analysis. Note that in clerical applications, there are sometimes revenue increases instead of cost reductions. For instance, faster invoicing by computer increases the interest revenues.

MIS computer projects affect immaterial outputs: Data is collected and transformed by the MIS into information on which decisions are based which either reduce operating costs (wages, machinery costs, inventory carrying costs, etc.) or increase sales revenues. Against these benefits we have to weigh the data processing cost of the MIS. It is useful to distinguish between operational and strategic/tactical decisions.

(1) Operational decisions are short-term, lower management decisions. Since these decisions are relatively well-structured they can be easier modeled (and even programmed partly). Having built such a model, say an inventory control model, it is a rather straightforward OR exercise to

study the effects of improved information quality. For instance, POS terminals increase the accuracy of data and consequently decrease the safety stock; more frequent inventory reviews (based on computer data instead of physical inventory counting) reduce both working stock and safety stock; [37]. Other examples are provided by airline reservation systems which dampen capacity requirements, and cash and debt management by banks which reduce interest loss and risk; see [72].

(2) Tactical and strategic decisions are longer-term, higher-management decisions. These decisions are ill-defined so that they cannot be computerized. Nevertheless computers may provide assistance. They can supply computational power for, say, corporate simulation models, possibly run in the interactive mode. Computers can further supply a wealth of data, possibly allowing browsing through the data base using a DBMS. (As we mentioned above, some data may be collected ad hoc from external sources, say, governmental sources.) Modeling strategic and tactical decisions is much more difficult, since these processes are known to be ill-structured, and are not very well understood. We would add that it is always hard to model processes that involve the interaction between the company and its environment (competitors, customers, etc.). The internal operations are better understood (and hence controlled). Even in inventory management we see that loss of goodwill caused by disservice is very difficult to model. For a discussion of MIS and operational versus strategic decisions and structured versus unstructured decisions, we refer to [29,36].

Even though is is difficult to model the benefits of a MIS, we would argue that it should be tried. Strategic decisions like major investments are difficult too, but nevertheless models are used as a decision aid (not meant to automate strategic decision making!). Without formal models, a MIS project will also be evaluated but then in a subjective way using mental models that are hard to communicate and to criticize. We shall briefly discuss several approaches to the formalization of the cost/benefit evaluation of a MIS.

(1) Bayesian decision analysis or Information Economics
Bayesian decision analysis goes back to the work by Raiffa and Schlaifer [58,60]. Its application to the evaluation of information has been pioneered by Marschak [43,44] under the name Information Economics. This theory highlights the following factors affecting the value of information.

(i) Surprise content of information: Information that has already been expected, does not have much value. This surprise content is "measured" by the difference between the "prior" and the "posterior" probability distribution. The prior distribution is based on the information available before additional data is collected (using a MIS). The posterior distribution is computed by combining the prior distribution with the additional data, applying a theorem developed by Bayes.

(ii) Effect of the information on the decision: The decision analysis is based on a payoff matrix, showing the payoffs (revenues) for each combination of decision (action, say, production size) and state of nature (say,demand volume). If we take the same action regardless of the probability distribution of the states of nature, then additional information on that distribution is worthless. An upper limit for the gross benefits of a MIS is the value of perfect information. The net benefit of a MIS is the gross value of the (imperfect) information it yields, minus its costs.

(iii) Effect of the decision on the benefits: The benefits may be insensitive to the action we take, i.e., the rows (corresponding with the action) of the pay-off matrix may be identical. Relative insensitivity is familiar in inventory control where the total cost is quite insensitive to the exact values of the cost parameters occuring in the square root formula.

Information Economics ha a number of limitations:
(a) Many data are needed for the decision calculus, namely a complete payoff matrix.
(b) The calculus can pose difficult mathematical problems, especially if we try to meet the following criticism.
(c) The physical production system controlled by the MIS, is highly simplified. Actual systems show interrelated production processes (purchasing, various production stages, sales, etc.), irregular (triggered) decision-making, and dynamic behavior (actions affect states of nature, etc.).
(d) The analysis concentrates on a single information characteristic, namely accuracy.
Applications of Information Economics can be found at the strategic level (say a major investment decision) where limitations (c) and (d) are less restrictive. Some rather simplistic models for inventory operations have been derived too; [66]. For additional details and references we refer to [33,36,72].

(2) Industrial Dynamics or Systems Dynamics
Industrial Dynamics, currently better known as Systems Dynamics, was pioneered by Forrester [26]. It is a general view of the world, not especially developed for MIS evaluation. Its philosophy is that each sociotechnical system can be viewed as a dynamic system with feedback, i.e.,the system output is compared to a normative value, and if deviations are detected, one or more inputs are changed so that, hopefully, the deviations diminish. Collecting data, comparing to the norm, and changing the decision variables takes time. These time lags make the model dynamic. Technically, the model consists of recursive

difference equations with variable coefficients or "rates". DYNAMO is the computer language especially developed to simplify the programming of Industrial Dynamics Models, but simulation languages like CSMP can also be used.

Lags in information transmission cause fluctations in the company's activities, as opposed to external business cycles, [8]. In a few studies the effects are studied of information delays, and accuracy; [67]. Industrial Dynamics does not pretend to give exact numerical predictions, but shows qualitative dynamic properties like explosive growth. It uses rather aggregated models with continuous relationships, i.e.,no discrete events, no triggers; [72,74].

(3) Simulation and Gaming

Simulation and gaming (simulation with human participants) are just techniques, so that the ideas (research topics) must be provided by theories like Information Economics, Industrial Dynamics, and more general disciplines like economics and information science. Simulation permits the numerical evaluation (solution) of non-linear, dynamic, stochastic models, either very detailed (discrete-event simulation programmed in, say, GPSS or SIMSCRIPT) or more aggregated (difference equation models as in corporate simulation). If certain aspects like fuzzy criteria and decision rules, are too elusive for modeling, we can have real people act as "models" of, say, managers: gaming.

There is a growing body of simulation and gaming experiments with MIS, investigating the multiple effects of various structures of the MIS, and quality attributes like timeliness, accuracy, aggregation level, presentation mode, and so on. For simulation we refer to [6,7,36,72]; for gaming see [22,51]. Welke [74] criticizes the ad hoc character of these simulation and gaming experiments, and proposes a general framework for the simulation modeling of information systems. In [36] we give more details on the various techniques and theories for the cost/benefit evaluation of a MIS.

COMPUTER PERFORMANCE AND OR

The previous sections focussed on the user aspects of computerized information systems, and the top-management evaluation of a MIS. In the present section we return to the computer *per se*.So we discuss the design, evaluation and tuning of computer systems, the performance criteria being technical measures like throughput, response time, and reliability (availability). This is a well-established discipline with its own organizations like the Special Interest Group on Measurement and Evaluation (SIGMETRICS) of the ACM. Publications in this field are abundant; see the long bibliography [2].

Technical computer performance can be approached by OR modeling, or by other techniques. These "other" techniques will not be discussed here: See [2,24,31,41] for benchmarks, kernels, instruction mixes, etc. OR techniques are often more accurate since they can represent interactions among computer programs in a multiprogramming system. OR models do not require the physical availability of a computer as benchmarks do. Let us have a closer look at some OR techniques.

Queuing theory has been extensively applied to computer systems. Conversely, this has stimulated new developments in queuing theory, for instance, networks of queues; see also [18]. Application areas are CPU scheduling algorithms for multiprogramming operating systems, data management (allocation of primary and secondary memory, disc organization), computer networks, and so on; [30,31,38,57] . These references also discuss other analytical techniques like reliability modeling.

Simulation is applied if the model has to be more realistic. For instance, a time-sharing model may reflect many queuing, job shop, and allocation problems: when to execute which program, where to store programs and data, etc. Many such systems are studied by discrete-event simulation. Trace-driven simulation uses as input the empirical data obtained through the execution of actual programs on a particular computer, these data being generated by tracing the computer programs. This input is processed by a model simulating alternative computer systems. Usually trace-driven simulation models are less detailed than stochastic, discrete-event simulation models. Much software is available for simulation. Simulation languages like GPSS and SIMSCRIPT facilitate the simulation of any discrete-event model (computers, hospital services, etc.). There are also languages especially developed for the simulation of computer systems, for instance, ECSS, CTSS, OSSL, QAL. Moreover, complete packages like SCERT, CASE, and IMSIM, are available so that the user has to specify only his parameter values. Observe that the input data for simulation or analytic models of computers, can be provided by the computer itself, in so far as data on an existing system are concerned: Hardware and software monitors measure the computer's own activities. For additional discussion and references we refer to [24,31,36,39,42,64],

OR can be relevant not only in the design and evaluation of computer systems, but also in the day-to-day operations of a computer center. A computer center is like a job shop: There are a number of jobs, each job having its own requirements for CPU, printer, etc. Hence it must be decided when to execute which job. This scheduling may be assisted by OR models; [15,16].

More economical than technical (computer) oriented, are LP formulations trying to minimize data processing costs by the optimal configuration of the total computer system; [30]. However, such mathematical programming formulations remain very unrealistic. Practical configuration problems are attacked by, for instance, packages like SCERT.

CONCLUSIONS AND LOOK AHEAD

Computers and OR show many interdependencies. Both began their development during and immediately after World War II. The computer's tremendous growth in speed and memory capacity, together with its reduced costs enabled number - crunching OR models like LP, simulation, inventory models. Software, however, continues to pose problems because of its costs and complexity. More recently, the development of on-line, interactive computer systems and DBMS have stimulated heuristic and man-machine problem solving. This new approach reduces the practicality gap between management science and management practice. In the near future we may expect more user-friendly software like problem-oriented query languages. OR modeling may show more practical and higher level applications if management becomes more quantitative and model oriented. Such a management style may be stimulated by management education at the university level, and by the general quantification of our society through the increased use of computers! See also [4, 23].If OR becomes more accepted by management, then it remains the task of OR scientists to develop relevant models. Robust models will be needed, i.e., models that accept a wider variety of assumptions, not just, say, exponential service times. Models of wider scope will be needed too, i.e., models not representing inventory costs of a single article but models covering inventories of many articles, stocked at different geographic places, combined with production, transportation, and purchasing. Approximate total-system's model may be of more relevance than exact optimizing subsystem models. Note that Systems Dynamics and General Systems theory have always emphasized such a total-system's view. Once the models have been developed, the quantification of parameters and variables can be drastically facilitated by computers: Point-of-Sale terminals, data bases with DBMS facilities, data bases connected in networks, etc.

Quantifying the benefits of computer projects is an area where much work remains to be done. Information Economics provides beautiful theory but requires more work to make it operational. It might be integrated with theoretical frameworks provided by Systems Dynamics, general information science, and related disciplines. Solutions of the resulting models can be obtained by simulation so long as analytical solutions have not been developed.

The use of modeling in the design, evaluation, tuning, and operation of computer systems is a well accepted discipline. Its practical application (say, fixing an operating system's parameters) is lacking behind.

Note that computers play a special role in OR in so far as they can be used to teach OR via business games (well accepted) and Computer Assisted Instruction (not yet realized in OR teaching). Research and applications would be stimulated by having on-line retrieval of OR publications and models from a data bank. See also [46].

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